

Is Stress Quantum-Like?

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Abstract. In this paper we examine two well-controlled experiments where order effects were shown under stress. We show that for only one of those experiments the QQ equality of Wang and Busemeyer [21] seems to be fairly satisfied (under independence assumptions). Since the experiment satisfying QQ measures physiological variables, this may suggest that quantum order effect outside human judgment models.

1 Introduction

It is a well-known fact that the order in which two questions are asked affects the frequencies of their answers. Question order effects are observed by presenting two questions, Q_1 and Q_2 , to two similar populations but in different orders. To one group, Q_1 precedes Q_2 , whereas to the other group, Q_2 precedes Q_1 . If there are changes in the frequencies for the answers to the questions between groups, then we see an order effect. This is known as the order effect, and it has been the subject of interest and study of social scientists for a while. Another well-known fact is that order effects also exist in physical measurements, in particular in quantum mechanics, where order effects exist *in principle*. They are associated to the existence of complementary variables whose observable operators in the Hilbert space do not commute, and therefore cannot have a simultaneous projector basis yielding repeatable experimental outcomes.

The main difficulty behind order effects is that they seem to violate standard probability theory, where the expectation of a random variable does not depend on which order we observe it. Therefore, it should not come as a surprise that among the first successful attempts to use quantum-like models in the social sciences were ones related to order effects. Furthermore, one may argue that all quantum-like effects in social sciences are actually order effects, mainly for two reasons. First, no experimental situation can preclude subliminal communication as a means of creating the superclassical (quantum-like) correlations, and therefore it is always possible to think of causal classical mechanisms that

lead to such correlations. This means that the effects on the context-dependent probabilities could be seen as caused by this (perhaps difficult-to-observe) order. Second, it seems that all violations of contextual (Bell-type) inequalities may be explained by direct influences between the observables [11], which would be modeled in physics by order-effect like computations.

Be that as it may, quantum-like order-effect models make non-trivial predictions. For instance, in their seminal paper, Wang and Busemeyer [21] showed that for order effects described by the collapse of a state vector, the diagonal terms of the order effect matrix (see Section 2) would add to zero. This result is known as the Quantum Question (QQ) equality, and it not only holds for order effect models that use projections in a Hilbert space, but also for a vast set of data examined in [22].

In this paper we investigate order effects in stress. Stress can be thought of as, among other things, be caused by conflicting conditions. This is what is often seen in cognitive order effects, where the order of questions changes the assessment of the subsequent question. Here we investigate two experiments showing order effect under stress: one involving decision making under stress, and another measuring physiological effects. In both cases, the data suggests that the QQ equality is satisfied, thus supporting the idea that order effects are better described by quantum probabilities.

2 Quantum-like order effects and the QQ equality

In this Section, we will discuss how the Hilbert space quantum formalism leads to the order effect, in the same way that it is applied to the QQ model. For our purpose it suffices to examine a simple case. Imagine two propositions about the system of interest, P_A and P_B . Such propositions can be either true or false, depending on the state of the system. For example, P_A can be the question “Is the spin in direction $\mathbf{z}$ equal to $+1/2$?” To know whether this is the case, a spin measurement must be made, and the outcome would be either “yes, it is equal to $+1/2$,” or “no, it is not equal to $+1/2$,” in this case the system of interest would be a particle with spin. P_B would then be a question that probes the same Hilbert space, e.g. “Is the spin in direction $\mathbf{e} \neq \mathbf{z}$ equal to $+1/2$?” Another example outside of physics, discussed in [22], is when P_A is the question “Is Bill Clinton honest and trustworthy?” and P_B is “Is Al Gore honest and trustworthy?” The system of interest here is a participant in an opinion pool, who may answer the question in the positive or negative.

To represent the stochastic outcomes of answers for the above cases, we use a standard quantum model for order effects (see [15,4,12]). We start with two yes-no questions, Q_A and Q_B , and associate to them projector operators $\hat{P}_A$ and $\hat{P}_B$ in a Hilbert space, $\mathcal{H}$. Because there is an order effect, originated from the impossibility of simultaneously measuring Q_A and Q_B , we assume that $[\hat{P}_A, \hat{P}_B] \neq 0$ (we remark that non-commuting operators are typical in quantum descriptions of cognitive systems). Prior to the first question, the participant’s “cognitive state” may be represented by a quantum mixture ρ . However, after a

question is asked, this state collapses into either $\hat{P}_i \rho \hat{P}_i$ or $(\hat{1} - \hat{P}_i) \rho (\hat{1} - \hat{P}_i)$, $i = A, B$, with the former expression corresponding to “yes” to question Q_i and the latter to “no.” This new collapsed state is then measured again, by $\hat{P}_j$, $j \neq i$.

To understand where the order effect comes from, consider the example where the quantum state is not a proper mixture, but a pure state $\rho = |\psi\rangle\langle\psi|$ (where $|\psi\rangle$ is a vector in the Hilbert space and $\langle\psi|$ its associated dual vector) that is measured first by P_A and then by P_B . What is the probability that $P_A = 1$ and $P_B = 1$, when measured in that order? The probability that P_A is one is given by $p(P_A = 1|\rho) = \text{Tr}(\rho \hat{P}_A)$, and when such value is measure, the quantum state collapses to $\hat{P}_A \rho \hat{P}_A / \text{Tr}(\rho \hat{P}_A)$. Now, the probability of $P_B = 1$ for the state $\rho = |\psi\rangle\langle\psi|$ is $p(P_B = 1|\hat{P}_A|\psi\rangle) = \langle\psi|\hat{P}_A \hat{P}_B \hat{P}_A|\psi\rangle / \langle\psi|\hat{P}_A|\psi\rangle$. Therefore, the answer to our question is simply

$$p_{a:b} = \langle\psi|\hat{P}_A \hat{P}_B \hat{P}_A|\psi\rangle,$$

where we introduced the notation where $p_{a:b}$ corresponds to the probability of $P_A = 1$ followed by $P_B = 1$, $p_{b:\bar{a}}$ to $P_B = 1$ followed by $P_A = 0$, and so on. From similar computations,

$$p_{b:a} = \langle\psi|\hat{P}_B \hat{P}_A \hat{P}_B|\psi\rangle,$$

$$p_{\bar{a}:\bar{b}} = \langle\psi|(1 - \hat{P}_A)(1 - \hat{P}_B)(1 - \hat{P}_A)|\psi\rangle,$$

and

$$p_{\bar{b}:\bar{a}} = \langle\psi|(1 - \hat{P}_B)(1 - \hat{P}_A)(1 - \hat{P}_B)|\psi\rangle.$$

Since $\hat{P}_A$ and $\hat{P}_B$ do not commute, it follows that $p_{a:b} \neq p_{b:a}$, which is what we understand as an order effect: the probability of answer P_A is different when asked before or after P_B .

From systems that present order effect (or any system, for that matter), we can define an effect size matrix

$$E = \begin{pmatrix} p_{a:b} - p_{b:a} & p_{\bar{a}:b} - p_{b:\bar{a}} \\ p_{a:\bar{b}} - p_{\bar{b}:a} & p_{\bar{a}:\bar{b}} - p_{\bar{b}:\bar{a}} \end{pmatrix}.$$

This matrix reflects how much the probabilities change given the order: if there are no order effects, then E is the zero matrix; if the elements of E are large, then there is a strong order effect, as the expectations change considerably with orders. Notice that E has nothing to do with a quantum model, as it expresses the order effect in terms of measurable probabilities. However, from the above quantum model, it is straightforward to compute, from the algebra of projection operators (mainly their idempotent property), that the diagonal term sums to zero, i.e.,

$$q = (p_{a:b} - p_{b:a}) + (p_{\bar{a}:\bar{b}} - p_{\bar{b}:\bar{a}}) = 0.$$

This is called the QQ equality by [22], and it is exactly satisfied by quantum systems.

It is striking that most order effects in psychology seem to satisfy the QQ equality. In their paper [22], Wang et al. examined 72 datasets related to order effects to opinion-pool questions (the Clinton and Gore question above was part of a Gallup pool). With the exception of a few (pathological?) cases, the vast majority of the data satisfied the QQ equality. Perhaps more telling, Wang et al. [22] examined alternative models used to describe order effects, and none of them main alternatives in the literature fit the QQ equality. In the next section we will discuss order effects in the stress literature, and show not only that the QQ equality is satisfied in decision-making under stress, but also for physiological outcomes.

3 Order effects in Stress

Order effects are well established in stress research, thought with perhaps a different meaning from the ones discussed above. For instance, a physiological response seems to change with time in almost every cases of emotional responses, and repeating the same stimulus frequently decreases or increases a response, which just depends on the stimulus type. In the case of stimuli inducing adaptive behavior, most usually positive stimuli, repeating of the stimulus usually leads to a decreased response, which is called habituation (e.g. delicious food everyday) [3,20]. In cases of maladaptive responses most usually stressful stimuli, a frequent type of response is "sensitization" [10,14], i.e. a progressively increasing response to the same stimulus. Additionally, there is evidence that those types of responses work also for electric stimulation of the brain: upthreshold stimulus usually leads to epileptic discharges due to increasing responsibility to subthreshold stimuli related to "sensitization," and consequently very small sub-threshold electric stimulus at later times may cause epileptic discharges [16,18].

The order effects in the above paragraph present two challenges to testing the QQ model. First, it is not immediately clear how they actually correspond to the standard idea of order effect as modeled by a collapse of the wave function, since they do not seem to correspond to successive "measurements" (in the quantum sense) of two different operators. Second, as far as we know, and related to the first issue, they do not provide data sets that can be used to observe the QQ equality. For these reasons, we focus here on two well-controlled experiments with human subjects where order effects are shown: one where behavioral outcomes change with the order of stressors, and another where physiological outcomes did as well. In the subsection below, we describe the relevant experiments analyzed here. Then, in the following subsection, we analyze the QQ equality, showing that it is apparently satisfied also for those two experiments.

3.1 Order Effect Experiments

Well controlled experiments that provide enough information to allow for the computation of order effects in situations under stress are not widely available. At least as far as the authors can tell, the only (human) experiments that are set

under the necessary criteria that allows us to estimate the QQ equality from the available published data are the experiments of Banis and Lorist [1] and Caceres and Burns [5]. We describe them briefly in the subsections that follow.

Behavioral order effect in stress. In an interesting work, Banis and Lorist [1] studied the impact of acute noise stress on the feedback-related negativity (FRN), and whether the predictability of the stressor affected the results. FRN is an event-related potential (ERP) electroencephalogram component that is triggered by external feedback. Banis and Lorist used loud white noise, a stressor known to activate the hypothalamic-pituitary-adrenal axis and sympathetic nervous system that increases stress hormones, thus affecting the activity in brain areas responsible for feedback evaluation. Their goal was to test if acute noise stress had any influence on the cognitive control functioning of the anterior-cingular-cortex (ACC) through the analysis of the FRN feedback, and if the results depended on the predictability of the noise stressor. In their experiment, 32 healthy male undergraduates participated in an experiment where they performed a gamble task. Each trial started with a cross displayed at the center of a computer screen. After 500 ms, two white rectangles were displayed to the left and right side of the cross. Those rectangles remained on the screen until the subject selected one of them by pressing a button with their left or right index finger, corresponding to the equivalent location of the rectangle selected. The selected rectangle was then highlighted with a thick yellow border, for a random time interval between 800–1200 ms. After that, the highlighted rectangle was filled with one of two colors, cyan or magenta, corresponding to monetary gain or loss. Which color was associated with gain or loss varied across participants. Simultaneously to the appearance of cyan or magenta, the amount of gain or loss (± 5 or ± 25 cents of Euros) appeared inside the selected rectangle, informing the participant of how much money they won or lost during that trial. The values displayed inside the rectangles were selected randomly with equal probability for all of four possible values (though participants were not informed of this). This feedback was displayed for 1000 ms, and after that the next trial started. The experiment was conducted with five-minute trial blocks separated by 15 minutes of rest. Some trial blocks were performed first under a noise stressor, consisting of a discontinuous (75-95 dB) or continuous (85 dB) white noise, with intervals varying between 2 to 7 seconds, and then in silence; other blocks had the reverse order. Silence and noise condition trials were counterbalanced across subjects, with participants performing an equal number in each condition. At the beginning of the experiment, participants started with a balance of 5 euros, and were instructed to select whichever strategy they wished to maximize their gain: whatever balance they had at the end of the experiment was theirs to keep. At the end of each block, participants were informed about the amount of money they earned in the previous block. Though this experiment’s main goal was to measure the effect of acute stress as a decreased in cognitive control by the ACC, it also showed that mean reaction time and mean stay percentages

(i.e., how often a participant selected the same response as a strategy) depended on the condition order of the block (silence-noise vs. noise-silence conditions).

Physiological Order Effect in Stress. Many studies have shown a correlation between stress-induced physiological reactivity and indexes of pain sensitivity, but there was no proof whether such reactivity could affect consecutive levels of pain threshold, tolerance, and self-reported severity. To answer this question, Caceres and Burns [5] investigated if the indexes of pain sensitivity were influenced by physiological reactivity (namely, blood pressure and heart rate) induced by acute noise as a psychological stressor. To test that hypothesis, 52 individuals were randomly selected to perform one of two experimental protocols: mental arithmetic (MA) task followed by a cold pressor (CP) task or vice versa (we will refer to those two orders as MA/CP and CP/MA, respectively). Subjects were classified into low/high heart rate (HR) and low/high mean arterial pressure (MAP) based on reactivity to MA. The expectation was that stress-induced physiological changes would be able to modulate pain sensitivity. In such situation, the degree of sensitivity to pain could be predicted for the following task, since subjects with a high level of reactivity to the MA task would be more susceptible to exhibit characteristic pain threshold, tolerance, and self-reported pain severity. A second topic investigated was the hypothesis that there is a causal association between a presumed stress-pain mechanism evoked at the time of the initial task and pain sensitivity during a posterior task, or whether a common cause could explain both the presumed mechanism and subsequent pain. Their results showed that stress-induced MAP reactivity was related to pain threshold and tolerance only for subjects who received the MA task in the first phase of the experiment. In addition, their results showed that subjects in the MA/CP condition with high MAP increases during the first MA task exhibited a lower pain threshold and tolerance in a posterior CP task than low MAP reactors in the same condition. In the CP/MA case, the high and low MAP reactors the pain index had no significant differences. For high MAP reactors to the MA task in the MA/CP case had a lower pain threshold and tolerance if compared with high MAP reactors to the MA task in the CP/MA case. In other words, the mean arterial pressure under CP or MA presented an order effect.

3.2 QQ equality in Stress

In this subsection we examine the order effects observed in [1,5], in particular whether they satisfy the QQ model, in terms of obeying the QQ equality (how well the model fits the data is not interesting here, since the number of parameters for the quantum model is fairly large). Let us start with the data from [1], who report a strong and statistically significant order effect for the behavioral component of their experiment, where the mean stay percentage was observed. So, in terms of order effect, we have the following two random variables, S_N and S_S , corresponding to “Was the strategy, under noisy condition, to repeat the last response?” and “Was the strategy, under silence condition, to

Silence-Noise			Noise-Silence		
	$\mathbf{S}_N = 1$	$\mathbf{S}_N = 0$		$\mathbf{S}_N = 1$	$\mathbf{S}_N = 0$
$\mathbf{S}_S = 1$	.5289	.1323	$\mathbf{S}_S = 1$	.3859	.2084
$\mathbf{S}_S = 0$	.1388	.2000	$\mathbf{S}_S = 0$	.2000	.2057

Table 1. Data, adapted from [1].

repeat the last response?” Averaging over the mean stay percentages for large and small gains, given that trials were balanced, we obtain for the silent-noise order, $E(\mathbf{S}_N) = 0.665$ and $E(\mathbf{S}_S) = 0.665$, and for the noise-silence order $E(\mathbf{S}_N) = 0.545$ and $E(\mathbf{S}_S) = 0.558$. There is a clear order effect. To compute the order effect matrix E , we need to know the complete probability of events in both situations, namely, e.g., what is the probability that $\mathbf{S}_N = 1$ in the first half and $\mathbf{S}_S = 0$ in the second, what is the probability that $\mathbf{S}_N = 1$ in the first half and $\mathbf{S}_S = 1$ in the second, and so on. To do so, we obtained the original set of data from the authors, and computed the outcomes in Table 1.⁴ From this data, we can compute the order effect matrix,

$$E_{BL} = \begin{pmatrix} .1430 & -.0761 \\ -.0612 & -.0057 \end{pmatrix},$$

which gives a $q = 0.1373$, which does not corroborate the values predicted by quantum models.

More interesting than the previous result, however, is the experiment by Caceres and Burns, as it shows an order effect in physiological data, namely the mean arterial pressure (MAP). Once again, the data provided in [5] was the mean values of MAP (in *mmHg*) and their corresponding variance. We used this data to estimate, assuming a log-normal distribution for MAP [24], and comparing to the provided baseline, the probability for the following two questions, represented by the random variables $\mathbf{P}_M$ and $\mathbf{P}_C$: “Was the mean arterial pressure above the baseline under the mental arithmetic task?” and “Was the mean arterial pressure above the baseline under the cold pressor task?” The estimated probabilities are given on Table 2. Once again, the order effect matrix can be computed from

MA/CP			CP/MA		
	$\mathbf{P}_M = 1$	$\mathbf{P}_M = 0$		$\mathbf{P}_M = 1$	$\mathbf{P}_M = 0$
$\mathbf{P}_C = 1$	0.3403	0.1627	$\mathbf{P}_C = 1$	0.2935	0.1616
$\mathbf{P}_C = 0$	0.3362	0.1607	$\mathbf{P}_C = 0$	0.3514	0.1935

Table 2. Order effect data for MA/CP and CP/MA conditions, adapted from [5].

⁴ The assumption of statistical independence are possibly false. However, it is not possible to reconstruct the joint probability from the marginals without some additional assumptions.

Table 2, yielding

$$E_{CB} = \begin{pmatrix} 0.0468 & 0.0011 \\ -0.0151 & -0.0327 \end{pmatrix},$$

which gives a $q = 0.014$, also close to quantum models.

4 Final remarks

In this paper we examined two experiments in stress that observed order effects. For the Banis and Lorist experiment, we obtained the original data set and computed the joint probability distribution from it. For the other experiment examined, from the published data, we constructed (under simplifying conditions) data tables that allowed us to define an order effect matrix, from which the QQ equality could be computed. We saw that for the Banis and Lorist paper, the sum of the diagonals of the effect matrix was far from zero, thus not supporting the idea that the QQ equality holds, whereas for the simplifying assumptions used here the Caceres and Burn experiment satisfied the QQ equality. This shows that the QQ equality may be satisfied for some physiological experiments, though our results do not support it.

Our results relate to the broader literature in mental disorder that identifies disturbances in the synchronization connecting different regions of the brain [6,2]. For instance, quantum-like effects may appear in phase-synchronization models where incompatible stimuli are presented simultaneously [8,7,9]. Such quantum-like effects are similar to the order effects discussed, and recent studies on brain dynamics under stress conditions [23,17,13,19] suggest a decrease in synchronizing patterns compatible with those modeled in reference [8].

Our conclusions are limited, for many reasons. First, because of our limited access to experimental data limited to publicly available results in the literature, we could only obtain the order-effect matrix under very simplifying assumptions which are likely not true. Furthermore, without the actual data (except for [1]), we could not perform a χ^2 test to verify whether satisfying the QQ equality was done in a statistically significant way (that order effects were present were reported with statistical significance on the original papers). Second, the experimental protocols used in [1,5] were not conducive to accurately measure the order effect in a way defined by [21]. For example, the QQ equality was derived from quantum models where you have an ensemble of participants from a same population, and the first experiment does not fit this criteria. So, even with the raw data from experiments, we would expect to have problems constructing the data in Tables 1 and 2. Finally, we should point out that the data is not within subjects, so our conclusions for within subjects should be taken with a grain of salt.

As such, this paper should be seen only as an indication that quantum-like probabilistic order effects may possible not only for human judgments, but also that stress may affect such order effects. Furthermore, as we have seen, the quantum models seem to extend beyond human judgment, and fits with the description of order effects on the mean arterial pressure, a physiological variable.

This is an exciting result, if actually found to be true once further experiments are carried out, where such effects could be measured in a more precise way, as they would raise the question as to why quantum probability would be a good descriptor of such types of processes.

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